Sustainable Cities and Society 61 (2020) 102319

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Life-cycle environmental and cost-effective energy retrofitting solutions for office stock

Marta Gangolells, Katia Gaspar*, Miquel Casals, Jaume Ferré-Bigorra, Nuria Forcada, Marcel Macarulla

Universitat Politècnica de Catalunya·BarcelonaTech (UPC), Group of Construction Research and Innovation (GRIC), C/ Colom, 11, Ed. TR5, 08222 Terrassa (Barcelona), Spain

ARTICLE INFO

Keywords:
Office buildings
Energy retrofitting
Reference buildings
Representative offices
Life-cycle assessment
Life-cycle energy impact
Life-cycle economic impact
Life-cycle environmental impact

ABSTRACT

The European Green Deal establishes the need to renovate buildings in an energy efficient way, to address climate and environmental challenges. The purpose of this study was to devise a model for identifying environmental, cost-effective retrofitting measures by assessing their energy, economic and environmental impact when they are applied to the entire office stock. The methodology builds upon the energy performance certificate scheme to identify the life-cycle energy, economic and environmental impacts of a set of energy renovation measures for each representative office. The results can then be applied to the entire office stock. For any real office, a dozen characteristics are entered. Then, a user-friendly interface provides information about the expected performance of the renovation measures in that case along with the representativeness of the results. This methodology was implemented in a Spanish case study of 13,701 energy performance certificates. The findings showed that the most efficient energy renovation measures are heat pump replacement (18.1 %) and replacement of lamps with LEDs (14.4 %). Although the most effective retrofitting solutions depended on the evaluation criteria (energy, economic or environmental), 99.5 % of the cost-effective measures also reduced emissions during the life cycle.

1. Introduction

In response to the climate emergency declaration by the European Parliament (Buildings Performance Institute Europe (BPIE), 2019), buildings and cities need to be transformed to achieve 55 % emissions reduction by 2030 and to become climate neutral by 2050 (European Parliament, 2019).

The European Green Deal is the European Union's response to climate and environment-related challenges, and to implement the United Nations' 2030 Agenda and Sustainable Development Goals (United Nations, 2015, European Commission, 2019a). Considering that building stock accounts for 40 % of the energy used in the European Union (European Commission, 2019b) and 36 % of CO_2 emissions (European Commission, 2018b), one of the eight new initiatives established in the European Green Deal is building and renovating in an energy- and resource-efficient way. According to Buildings Performance Institute Europe (BPIE) (2017), 97 % of building stock needs to be upgraded to become highly energy efficient and obtain an A rating in the Energy Performance Certificate scheme.

Residential buildings account for 75 % of the total floor area of buildings in the European Union (Buildings Performance Institute Europe (BPIE), 2011) and have final energy consumption of 288 Mtoe (27.2 %) (European Union, 2019), whereas non-residential buildings represent 25 % of the total floor space and account for 14.5 % (154 Mtoe) of final energy consumption (European Union, 2019). Residential buildings have higher final energy consumption in absolute terms. However, in proportion to the floor area, non-residential buildings have higher energy use intensity (kWh/m^2). Therefore, the potential for energy saving and carbon emissions reduction is greater.

1.1. Literature overview

In recent years, several studies have been conducted on the energy renovation of non-residential buildings. In most cases, non-residential buildings are studied as a single group, without distinguishing the final end use (which could be commercial, administrative, educational, medical, etc.). Rysanek and Choudhary (2013) proposed a holistic method for adapting building energy models that includes an economic

* Corresponding author.
E-mail addresses: marta.gangolells@upc.edu (M. Gangolells), katia.gaspar@upc.edu (K. Gaspar), miquel.casals@upc.edu (M. Casals), jaume.ferre.bigorra@upc.edu (J. Ferré-Bigorra), nuria.forcada@upc.edu (N. Forcada), marcel.macarulla@upc.edu (M. Macarulla).

https://doi.org/10.1016/j.scs.2020.102319
Received 6 March 2020; Received in revised form 27 May 2020; Accepted 4 June 2020
Available online 12 June 2020
2210-6707/

Nomenclature

BPIE	Buildings Performance Institute Europe
TBC	Technical Building Code
NPV	Net Present Value
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
ICAEN	Catalan Institute of Energy
NBE-CT 79	Compulsory basic building norm regarding thermal conditions in buildings
A1-A4, B1-B4, C1-C4, D1-D3, E1	Climate zone based on winter climate severity (identified by a letter) and summer climate severity (identified by a number)
DHW	Domestic hot water
CALENER GT	General procedure for the energy rating of large tertiary sector buildings recognized by the Spanish government
CALENER VYP	General procedure for the energy rating of dwellings and small tertiary sector buildings recognized by the Spanish government
CE3X	Simplified procedure for the energy rating of existing buildings recognized by the Spanish government developed by Natural Climate Systems S.A.
HULC	General procedure for the energy rating of dwellings and tertiary sector buildings recognized by the Spanish government (Lider Calener unified tool)
P1-P47	Primary energy retrofitting measures
S1-S5	Secondary energy retrofitting measures
T1-T3	Tertiary energy retrofitting measures
PQ1, PQ2	Improvement energy retrofitting measure packages
BEDEC	Structured Database of Construction Elements
B1-B7	Representative offices in the dataset of office blocks and offices in industrial buildings
R1-R7	Representative offices in the dataset of offices in residential buildings

cost-benefit model for optimal retrofit decision-making. The method was implemented in an office building. Jradi, Veje, and Jørgensen (2017) developed a holistic energy model for energy renovation of Danish non-residential and public buildings considering construction topology, space geometry, thermal envelope, building systems, weather conditions, schedules and occupant behaviour. An office building case study in the University of Southern Denmark was considered, where seven renovation measures and control strategies and eight packages of measures were assessed with a dynamic building energy performance approach. The results showed that a comprehensive energy renovation package (comprised of efficient lights, daylight sensors in open spaces and corridors, roof and exterior wall insulation and managing heating set point schedules) could reduce the primary energy consumption from 176.11 kW h/m^2 to 70.44 kW h/m^2. Dotzler, Botzler, Kierdorf, and Lang (2018) carried out a project to develop automated tools for the inventory and evaluation of tertiary sector buildings with heterogeneous uses and a wide variety of construction characteristics, to help decision-makers during the energy retrofitting process. Mata, Kalagasidis, and Johnsson (2018) compared the potential for energy efficiency improvement, associated costs and greenhouse gas emission reductions, using the same modelling methodology in five EU countries (France, Germany, Spain, Sweden and the United Kingdom). This study included results related to ten energy conservation measures and six packages of measures applied to a set of representative buildings (residential and non-residential buildings). Researchers concluded that to understand EU building stock, each building must be analysed, due to the variability of the results. This is especially true for non-residential buildings, because of the limited availability of information. Patiño-Cambeiro, Armesto, Bastos, Prieto-López, and Patiño-Barbeito (2019) studied eleven Spanish university buildings in an Atlantic climatic zone. The researchers analysed two passive measures (replacement of windows and improvement of the building envelope) and two active measures (heating and lighting) and concluded that the latter were more effective environmentally and economically. Hjortling, Björk, Berg, and Klintberg (2017) conducted a study to define the current energy consumption baseline for non-residential buildings in Sweden using data extracted from the national database of energy performance certificates, including multi-dwelling buildings, rented commercial office spaces, schools, healthcare facilities, sports facilities, and hotels and restaurants. The researchers concluded that climate zones had less impact on energy consumption than type of building. They recommended different building codes for different types of end use since they detected a distinction between categories of buildings in the data.

Offices account for nearly a quarter of the total floor area (Buildings Performance Institute Europe (BPIE), 2011) of non-residential buildings, and have great saving potential because 60 % of them were built before 1980 (Stegnar & Cerovšek, 2019). Existing cost-optimal methodologies are often applied to a limited number of case studies. In addition, a small number of studies have targeted offices that are in warm climates, where overheating is often observed (Congedo, Baglivo, & Centonze, 2020). Congedo, Baglivo, D'Agostino, and Zacà (2015) presented a cost-optimal methodology applied to a nearly zero energy office building in a warm climate. The study considered a set of 256 combinations of measures (four types of walls and windows and eight technical systems: two for heating and cooling, two for ventilation, two for generation and four PV panels). The researchers concluded that the best performing solutions range from 76.4 to 77.3 kW h/m^2·year of primary energy consumption with 22 kgCO^2/m^2·year compared to the reference scenario. Pomponi et al. (2015) compared the life-cycle energy and environmental impact of two strategies for energy retrofitting of offices in the UK: a double skin façade and an up-to-standard single skin façade. The study was conducted by means of a dynamic simulation of an office building considering 128 scenarios. The researchers concluded that the double skin façade was the most successful option to reduce the life-cycle energy and environmental impacts for the sustainable renovation of offices façades. Bournas, Abugabbara, Balcerzak, Dubois, and Javed (2016) presented an approach for the energy renovation of office buildings during the design stage that consisted of two steps: an initial design stage where insulation and moisture issues for the opaque part of façades and the new interior layout were considered, and the optimization stage where the energy intensity, daylight utilization and heating and ventilation system were considered. Researchers demonstrated the implementation with a proposed set of tools in the context of a case study. Gustafsson et al. (2017) assessed the economic and environmental impacts of energy renovation packages for a typical office building in three European climates (Nordic, Continental and Mediterranean). Energy renovation packages included insulation, windows, energy generation and distribution systems and solar photo-voltaics, with a total of 255 renovation cases. Researchers concluded that a reduction in final energy cost of up to 74 % could be achieved in the Mediterranean climate, up to 77 % in the Continental climate, and up to 70 % in the Nordic climate, compared to the reference cases. Niemelä, Levy, Kosonen, and Jokisalo (2017) presented a study to determine cost-optimal renovation measures that could maximize environmental and energy performance and indoor thermal comfort conditions of office buildings built in the late 1970s and 1980s in cold climate regions. A Finnish case study was selected, and several combinations of renovation measures for district heating systems and ground source heat pump systems were considered. The results showed that when energy efficiency and thermal comfort conditions are costoptimally improved simultaneously, a return on investment of up to 65 % and a 63 % reduction in CO_2 emissions of operation could be achieved.

Although several international standards address sustainability in buildings, Jensen, Maslesa, Berg, and Thuesen (2018) found that few tools and decision-making systems are focused on building renovation. Specifically, there is a lack of simple tools. Hashempour, Taherkhani, and Mahdikhani (2020) performed a literature review of energy performance optimization of existing buildings that focused on significant information for decision-makers. They highlighted the need to develop decision-making tools to improve the energy efficiency of existing buildings, considering sustainability. Moreover, they suggested that energy renovation measures need to be examined in depth in different weather conditions.

In summary, the literature mostly refers to non-residential buildings as a single group, even though buildings have been found to perform differently according to their use (Buildings Performance Institute Europe (BPIE), 2011). Therefore, a specific analysis should be carried out to provide individual energy solutions adapted to each need (Hjortling et al., 2017; Rysanek & Choudhary, 2013) and specific use. Although offices have great saving potential, very few initiatives have focused on their renovation to minimize environmental impacts (Sharif & Hammad, 2019). Most research initiatives on offices are based on building models and analyse a limited number of energy retrofitting measures. The lack of information and user-friendly tools to support decisions related to sustainable building renovation was found to be a barrier to energy refurbishment (Hashempour et al., 2020; Jensen et al., 2018).

1.2. Aim

In this context, the aim of the study was to develop a model for identifying environmental, cost-effective retrofitting measures for the entire office stock by assessing the energy, economic and environmental impact using a life-cycle approach. The model was designed to be replicated in different geographical areas. To support decision-makers during the energy retrofitting process, a user-friendly interface was designed. The methodology relies on the energy performance certificate database. This methodology is illustrated within the scope of the Spanish office stock.

The paper is divided into the following sections: methodology, case study and results, and conclusions.

2. Methodology

The methodology developed in this research consists of four steps, as shown in Fig. 1.

2.1. Identification of representative offices for the entire existing stock

The heterogeneity of the building sector makes it difficult to identify individualized, environmental, cost-optimal energy retrofitting measures (Gangolells et al., 2020). Within this context, reference buildings are an effective tool for assessing energy efficiency measures for the entire building stock (Brøgger & Wittchen, 2018; Pistore, Pernigotto, Cappelletti, Gasparella, & Romagnoni, 2019; Schaefer & Ghisi, 2016), as indicated by Commission Delegated Regulation (EU) No 244/2012 (European Commission, 2012).

First, the energy performance certificate database is prepared by structuring and organizing data to guarantee that further analysis is adequate. Then, database variables that have a potential impact on energy consumption are preselected.

To ensure the robustness of the analysis, data are pre-processed by performing consistency checks. The data are enriched with the generation of additional variables using information from the database, and variables that have different magnitudes are normalized on a normal scale (0–1).

Third, the *k-means* clustering based grouping technique is applied to identify a representative, limited set of virtual office buildings. To apply this technique, a correlation analysis is conducted between the variable of annual non-renewable primary energy consumption per square metre and the pre-selected variables. The optimum number of variables is then determined. Then, the cluster centroids are obtained, which determine the virtual representative buildings for each cluster.

Finally, real reference offices are selected by identifying the energy performance certificate with the shortest distance to the centroid of each cluster. Subsequently, the representativeness of real reference offices is calculated by expressing the level of correspondence between the centroid of the cluster and the selected energy performance certificate.

More details on the identification of reference offices that are representative of the entire office stock can be found in Gangolells et al. (2020).

2.2. Identification of energy retrofitting measures

The second step in the methodology is to select primary, secondary and tertiary energy retrofitting measures that will be evaluated in the subsequent steps. Measures can be selected by expert judgement or according to the results of previous studies.

Primary measures are those intended to reduce the energy demand of office buildings. These may include façade insulation, roof insulation, intervention on façade gaps (windows and balconies), sunscreen placement and improvement of airtightness.

Secondary measures are those designed to reduce the energy consumption required to meet the energy demand of offices. They are aimed at reducing energy consumption of heating, ventilation and air conditioning systems, lighting or use of equipment (including IT devices and lifts). Secondary measures can include renovation of existing boilers and heat pumps, installation of aerothermal heat pumps, solar thermal technologies and geothermal heat pumps, replacement of existing lamps with more efficient ones and equipment upgrades. Measures related to domestic hot water are outside the scope of this study, as energy consumption for hot water is deemed negligible in offices (Gangolells et al., 2019).

Tertiary measures may include the implementation of building energy management systems and programmes to increase energy-efficient user behaviour.

Finally, the combination of more than one retrofitting measure is assessed. Generally, primary measures are interrelated, as they can share auxiliary means. However, secondary measures are often

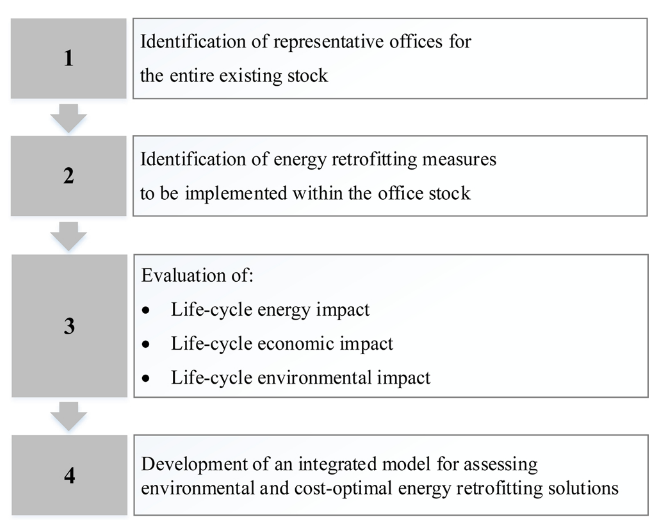

Fig. 1. Research methodology.

independent and can be executed in successive years according to priorities and needs.

2.3. Evaluation of the life-cycle energy impact

This step consists of evaluating the energy savings associated with the implementation of each retrofitting measure for each reference office. The simulation is conducted using the energy performance certificate file of each representative office and the corresponding official energy certification software. General energy certification procedures authorized by the Spanish Ministry for Ecological Transition and the Demographic Challenge (Spain, 2016) are preferred for the simulation due to their higher precision, but simplified procedures may be used if there is a lack of good representatives in the energy performance certificate database.

Energy savings are estimated by calculating the difference between the energy consumption of the original office and the energy consumption of the office after each retrofitting measure is applied (Eq. (1)):

$$EnS_g = En_{base} - En_{ERS} \tag{1}$$

Where EnS_g are the global energy savings, En_{base} denotes the total energy consumption of the reference office in the original state, and En_{ERS} indicates the total energy consumption of the reference office with the retrofitting measure implemented, all expressed in $kWh/m^2 \cdot year$.

2.4. Evaluation of the life-cycle economic impact

The economic analysis estimates the overall cost related to each retrofitting measure including the initial investment cost, the maintenance cost and the extra investment cost (Section 2.4.1). Economic savings provided by the energy savings are also considered (Section 2.4.2). Finally, the payback period is calculated (Section 2.4.3).

2.4.1. Evaluation of the cost of retrofitting measures

The overall cost of applying a retrofitting measure is calculated in accordance with the guidelines set out in Annex I of Delegated Regulation (EU) 244/2012 (European Commission, 2012), according to Eq. (2).

$$C_g(k) = \sum_j \left[C_I(j) + \sum_{i=1}^{k} \frac{C_{m,i}(j)}{(1+r)^i} \right] \tag{2}$$

Where $C_g(k)$ denotes the overall cost referring to the first year in the calculation period until the year k, $C_I(j)$ represents the initial investment costs of the measure or set of measures j (in €), $C_{m,i}(j)$ corresponds to the annual maintenance cost during year i of the measure or set of measures j (in €), r is the real discount rate, and k is an integer value ranging from 0 to τ in increments of 1.

2.4.1.1. Initial investment cost. For primary measures, the total initial investment cost (C_I) of a retrofitting measure depends on the area to be renovated, and is calculated following Eq. (3):

$$C_I(j)\ [primary\ measure] = c_{pm}(j) \cdot n_u(j) \tag{3}$$

Where $c_{pm}(j)$ is the unit cost of the primary measure j (generally in €/m^2) and $n_u(j)$ denotes the number of units of the primary measure j (generally in m^2).

The total initial investment cost (C_I) associated with secondary measures depends on the building energy power requirements, and is obtained in accordance with Eq. (4):

$$C_I(j)\ [secondary\ measure] = \sum_p c_{sm}(j,p) \cdot n_u(j,p) \tag{4}$$

Where $c_{sm}(j,p)$ is the unit cost of the equipment p of the secondary measure j (generally in *€/unit*), and $n_u(j,p)$ corresponds to the number of units of the equipment p of the secondary measure j (generally in *units*).

The total initial investment cost (C_I) in tertiary measures depends on each measure.

The estimated cost of energy retrofitting packages corresponds to the sum of the costs of the individual measures included within a package, minus the cost of shared auxiliary means.

2.4.1.2. Maintenance cost. The annual maintenance cost $C_{m,i}(j)$ can be considered void in the calculation of the net present value (NPV) and the payback period of the investment. In general, the implementation of energy retrofitting measures does not entail additional maintenance costs for the offices. In fact, the maintenance cost is practically the same, or even lower, if renovation measures are applied. If the maintenance cost is considered negligible, the total overall cost is constant throughout the retrofitting measure's life span.

2.4.1.3. Extra investment cost. Extra investment cost is defined as the difference between the initial investment cost of the energy efficiency measure and the cost of applying a conventional measure (Pikas, Thalfeldt, Kurnitski, & Liias, 2015). When energy refurbishment is carried out taking advantage of renovation of other structural or technical elements, the extra investment cost of adding energy retrofitting measures has a lower payback period, which significantly increases the profitability of the project (Institut Català de l'Energia (ICAEN), 2016).

Calculation of the extra investment cost depends on each specific measure. For primary measures, the extra investment cost is obtained by deducting costs that are already implicit in another renovation from the initial investment cost. For secondary energy retrofitting measures, the extra investment cost is the difference between replacing the old equipment with either conventional or high-efficiency new equipment. For tertiary measures, the initial investment cost is equal to the extra investment cost because there is no low-cost alternative.

2.4.2. Economic savings provided by energy savings

Energy savings (Eq. (1)) are translated into economic savings based on energy source prices.

The annual overall economic savings (EcS_g) provided by energy retrofitting measures are estimated using Eq. (5).

$$EcS_g(i) = [EcS_h(i) + EcS_c(i) + EcS_l(i)] \cdot A_{ref} \tag{5}$$

Where $EcS_g(i)$ indicates the annual overall economic savings in year i (in *€/year*),

$EcS(i)$ are the annual economic savings per unit area in year i in heating (EcS_h), cooling (EcS_c) and lighting (EcS_l), all expressed in €/m^2 *year*. A_{ref} represents the useful floor area of the reference office (m^2).

In any case, annual economic savings must be estimated considering the increase over time of the energy sources prices. Consequently, an annual mean increase should be considered. The energy price for a certain year is obtained according to Eq. (6).

$$P(i) = P_0(1 + PI)^i \tag{6}$$

Where $P(i)$ denotes the energy price in year i (generally in *€/kWh*), P_0 represents the energy price in the first year of the calculation period, and PI is the Energy Price Increase expected in the country of study. For electricity, the value of PI can be obtained through the European Commission (2018a). In other cases, the mean annual change in the Consumer Price Index in the study country over the last 5 years can be used.

2.4.3. Determination of the payback period

In this case and according to Delegated Regulation (EU) 244/2012 (European Commission, 2012), energy retrofitting measures are considered to have a 20-year life span.

Table 1
System boundaries defined as life cycle modules according to EN 15804 + A2 (European Committee for Standardization (CEN), 2019) and EN 15978 (European Committee for Standardization (CEN), 2011).

Information on the life cycle of the building															Additional information beyond the life cycle of the building			
A1-A3			A4-A5		B1-B7							C1-C4			D1-D4			
Product stage			Construc-tion stage		Use stage							End-of-life stage			Benefits and loads beyond the system boundaries			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3	D4
R-																			

aw material extraction
Transport
Manufacturing
Transport
Construction and installation process
Use
Maintenance
Repair
Replacement
Refurbishment
Operational energy use
Operational water use
Demolition
Transport
Waste processing
Disposal
Reuse
Recovery
Recycling
Exported energy

The initial investment payback period is given by Eq. (7).

$$PB = \left[\frac{-NPV(x-1)}{NPV(x) - NPV(x-1)}\right] + (x-1) \tag{7}$$

Where PB is the payback period (in *years*), $NPV(n)$ denotes the Net Present Value of the year k (in €), and x corresponds to the year that NPV becomes positive (in *years*).

The NPV is calculated for each year i of the next 20 years following the implementation of retrofitting measures. Considering that the annual maintenance cost $C_{m,i}(j)$ is considered negligible, the Net Present Value of each year can be calculated according to Eq. (8).

$$NPV(k) = -\sum_j C_I(j) + \sum_{i=1}^{k} \frac{EcS_g(i)}{(1+r)^i} \tag{8}$$

Where $C_I(j)$ indicates the initial investment cost for the measure or set of measures j (in €), $EcS_g(i)$ are the annual overall economic savings in year i (in €), and r corresponds to the real discount rate.

The payback period of the extra investment cost is also calculated according to Eq. (7), in which the initial investment cost of the measures ($C_I(j)$) is replaced by the extra investment cost of the measures ($C_{eI}(j)$) during the calculation of the NPV.

2.5. Evaluation of the life-cycle environmental impact

The life-cycle assessment (LCA) is conducted in compliance with ISO 14040 (International Organization for Standardization (ISO) & I, 2006), ISO 14044 (International Organization for Standardization (ISO), 2006) and EN 15804+A2 (European Committee for Standardization (CEN), 2019) standards, and consists of four steps: goal definition and scope (Section 2.5.1), life-cycle inventory analysis (Section 2.5.2), impact assessment (Section 2.5.3), and results interpretation (Section 2.5.4). The environmental impact of the retrofitting measures is assessed according to IEA-EBC Annex 56 (Almeida & Ferreira, 2017; Ott et al., 2017).

2.5.1. Goal definition and scope

The goal is to evaluate the environmental impact of the energy retrofitting measures proposed in Section 2.2 for the representative offices previously defined in Section 2.1. The functional unit will depend on the energy retrofitting measure (e.g. upgrade of 1 m^2 of façade by adding exterior wall insulation). As established in Annex I of Commission Delegated Regulation (EU) No 244/2012 (European Commission, 2012), the assessment is carried out for a reference study period of 20 years.

According to EN 15804+A2 (European Committee for Standardization (CEN), 2019) and EN 15978 (European Committee for Standardization (CEN), 2011) nomenclature, system boundaries include modules A1–A5, B1, B4, B6, C1–C4 and D3 (Table 1). Impacts linked to the removal and end-of-life of existing systems and elements are neglected as they are associated with the life cycle of the original building (Vilches, Garcia-Martinez, & Sanchez-Montañes, 2017; Wrålsen, O'Born, & Skaar, 2018). If an energy retrofitting measure has a lifetime shorter than the reference study period, replacements are considered.

2.5.2. Life cycle inventory

Construction databases are used to identify, for each energy retrofitting measure and corresponding respective life-cycle stages, a list of the tasks and required materials, transport processes, energy consumption and machinery operation. The operational energy use is calculated according to Section 2.3. Recommendations established by the Fraunhofer Institute for Building Physics (Gantner et al., 2015) are followed for the transport distances.

2.5.3. Impact assessment

The environmental impact is assessed through midpoint impact categories. All midpoint impact categories are calculated, but only global warming is presented to the general public (Wrålsen et al., 2018) as it has been shown that global warming is the only impact whose value does not change significantly depending on the LCA and LCI database used (Emami et al., 2019). In addition, the use of global warming eases the interpretation of results for the general public as it is a single, well-known impact. Infrastructure processes are excluded, and long-term emissions are included.

2.5.4. Results interpretation

Results extracted from the impact assessment are interpreted using the relative global carbon footprint reduction, calculated according to Eq. (9). This parameter provides a relative value that is easy for casual and expert users to understand.

$$Carbon\ footprint\ reduction\ (\%) = \frac{GW_{base} - GW_{ERS}}{GW_{base}} \cdot 100 \tag{9}$$

Where *carbon footprint reduction* is the relative global carbon footprint reduction expressed as a percentage, GW_{base} indicates the global warming impact caused by the representative office in the original state for the reference period (in $kg\ CO_{2eq}$), and GW_{ERS} denotes the global warming impact caused by the representative office with the retrofitting measure implemented for the reference period (in $kg\ CO_{2eq}$).

2.6. Development of an integrated model for assessing sustainable and cost-optimal energy retrofitting solutions

The last step consists of designing an integrated model that should allow users to assess which retrofitting measures provide greater energy savings with lower economic and environmental costs. The decision-making tool should decrease computational time and enhance reliability during the selection of optimal energy retrofitting packages (Hashempour et al., 2020).

A database is created by integrating data obtained in the previous tasks. For each reference office, the life-cycle energy, economic and environmental impacts of implementing all the aforementioned retrofitting measures are obtained. This information is gathered into a single database.

The user inputs the main characteristics of the office to be assessed and it is assigned into a cluster by normalizing basic data (Fig. 2). Then, the life-cycle energy, economic and environmental performance of the implementation of selected retrofitting measures in the corresponding representative office are shown. Finally, the level of similitude between the standardized characteristics of the office to be evaluated and those from the representative office is estimated through the degree of representativeness. As explained in Gangolells et al. (2020), the representativeness index is calculated according to Eq. (10):

$$Representativeness\ (\%) = \frac{\sum_{i=1}^{n} w_i \cdot (1 - |p_{i,ref} - p_{i,user}|)}{\sum_{i=1}^{n} w_i} \cdot 100 \tag{10}$$

Where n indicates the number of variables, w_i is the weighting coefficient of the variable i, $p_{i,ref}$ represents the value of the variable i in the representative office, and $p_{i,user}$ corresponds to the value of the variable i in the office to be evaluated.

3. Case study and results

The methodology was applied to a database of energy performance certificates compiled by the Catalan Energy Institute (ICAEN) between June 2013, when Royal Decree 235/2013 (Spain, 2013) entered into force, and July 2018. The database includes 13,701 energy certificates for offices. According to Krejcie and Morgan (1970) and considering that the existing population of office buildings numbers 47,121, the sample size is appropriate and representative, as detailed in Gangolells et al. (2020).

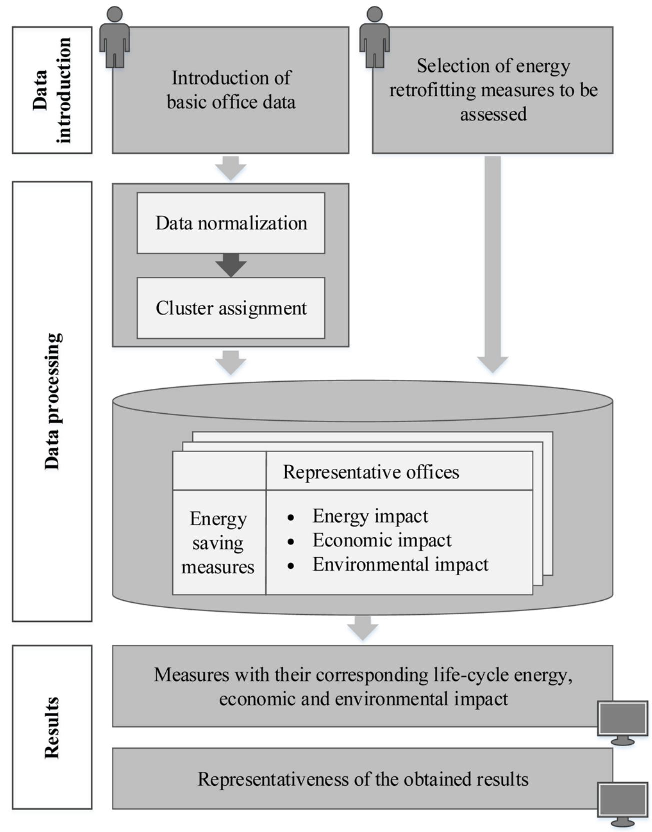

Fig. 2. Workflow for assessing life-cycle energy, economic and environmental impacts of energy retrofitting measures.

3.1. Identification of representative offices for the entire existing stock

An initial analysis of the database showed that most energy performance certificates corresponded to offices in residential buildings (76.58 %), while the rest corresponded to office blocks and offices in industrial buildings (23.42 %).

As the energy performance of these two office typologies is completely different, the database was disaggregated into two data subsets. The clustering-based grouping technique was applied to both subsets of data, so seven representative virtual office buildings for office blocks and offices in industrial buildings and nine virtual offices in residential buildings were identified. When the energy performance certificates that best matched cluster centroids had been selected, the degree of representativeness was calculated. As stated in the methodology, general procedures were prioritized over simplified procedures. The implementation of this technique using the Spanish energy performance certificates database is fully detailed in Gangolells et al. (2020).

Tables 2 and 3 summarise the main characteristics of the real representative offices for both the office blocks and offices in the industrial buildings subset, and the offices in the residential buildings subset. Climate zones are based on the classification proposed by the Spanish Technical Building Code (TBC; Spain, 2006). The Spanish TBC defines 16 climate zones based on their winter summer severity (represented by a letter ranging from A to E for the mildest and coldest winter, respectively) and summer climate severity (represented by a number ranging from 1 to 4 for the mildest and warmest summer, respectively) (Gangolells, Casals, Forcada, Macarulla, & Cuerva, 2016).

3.2. Identification of energy retrofitting measures

Considering the specific needs and characteristics of offices (e.g. occupational safety and health laws, low DHW demand or electricity as

Table 2
Characteristics of the representative office blocks and offices in industrial buildings.

Cluster	Useful floor area (m^2)	Shape factor (m^2/m^3)	Building regulation	Climate zone	Window glazing type	Wall insulation	Heating system	Heating energy source	Cooling system	Cooling energy source	DHW energy source	Certification tool	Representativeness (%)	Proportion of office stock (%)
B1	193.51	0.93	None	C2	Simple	Yes	No heating	No heating	No cooling	No cooling	No DHW	CALENER VYP	89.83	22.35
B2	7,513.76	0.31	None	C2	Double	No	Centralized	Electricity	Centralized	Electricity	Electricity	CALENER GT	86.83	14.07
B3	1,992.52	0.36	NBE-CT 79[a]	C2	Double	Yes	Centralized	Electricity	Centralized	Electricity	Electricity	CALENER VYP	89.49	29.51
B4	47.51	0.45	NBE-CT 79	C2	Simple	Yes	No heating	No heating	No cooling	No cooling	Natural gas	CE3X	99.97	5.04
B5	428.80	0.43	NBE-CT 79	D2	Low-e double	No	Individual	Electricity	Individual	Electricity	Electricity	HULC (CALENER VYP)	76.07	3.92
B6	1,724.21	0.46	TBC[b]	C2	Low-e double	Yes	Individual	Electricity	Individual	Electricity	Electricity	CALENER VYP	99.78	15.31
B7	89.00	0.37	NBE-CT 79	C2	Simple	No	Individual	Electricity	Individual	Electricity	Natural gas	CE3X	99.95	9.80

[a] NBE-CT 79 (Spain, 1979).
[b] TBC (Spain, 2006).

Table 3
Characteristics of the representative offices in residential buildings.

Cluster	Useful floor area (m^2)	Shape factor (m^2/m^3)	Building regulation	Climate zone	Window glazing type	Wall insulation	Heating system	Heating energy source	Cooling system	Cooling energy source	DHW energy source	Certification tool	Representativeness (%)	Proportion of office stock (%)
R1	127.00	0.34	None	D2	Simple	No	Individual	Electricity	Individual	Electricity	Electricity	CE3X	99.97	6.90
R2	22.15	0.26	None	C2	Simple	No	No heating	No heating	No cooling	No cooling	Butane	CE3X	98.75	0.84
R3	93.00	0.35	None	C2	Simple	No	Individual	Electricity	Individual	Electricity	Electricity	CE3X	99.99	42.43
R4	33.67	0.39	NBE-CT 79[a]	C2	Double	Yes	Individual	Electricity	Individual	Electricity	Electricity	CE3X	87.29	10.86
R5	64.70	0.49	NBE-CT 79	C2	Double	Yes	Individual	Electricity	Individual	Electricity	Electricity	CE3X	99.98	16.08
R6	42.31	0.08	None	C2	Simple	No	Individual	Electricity	Individual	Electricity	Electricity	CE3X	99.20	3.82
R7	401.55	0.16	NBE-CT 79	C2	Double	Yes	Individual	Electricity	Individual	Electricity	Electricity	CE3X	99.96	5.39
R8	172.00	0.27	None	C2	Simple	No	Individual	Electricity	Individual	Electricity	Natural gas	CE3X	99.91	9.63
R9	266.00	0.35	TBC[b]	C2	Double	Yes	Individual	Electricity	Individual	Electricity	Electricity	CE3X	99.98	4.05

[a] NBE-CT 79 (Spain, 1979).
[b] TBC (Spain, 2006).

Table 4
List of primary energy retrofitting measures and their corresponding code.

Group of measures	Measure code	Description of the measure
Exterior wall insulation	P1	EPS 6 cm
	P2	EPS 12 cm
	P3	XPS 6 cm
	P4	XPS 12 cm
	P5	Mineral wool 6 cm
	P6	Mineral wool 12 cm
	P7	Expanded cork 6 cm
	P8	Expanded cork 12 cm
Cavity wall insulation	P9	Graphite EPS 5 cm
	P10	Graphite EPS 10 cm
	P11	Glass wool 5 cm
	P12	Glass wool 10 cm
	P13	PUR injection 5 cm
	P14	PUR injection 10 cm
	P15	Pelleted cellulose 5 cm
	P16	Pelleted cellulose 10 cm
	P17	Injected cork 5 cm
	P18	Injected cork 10 cm
	P19	Sheep wool 5 cm
	P20	Sheep wool 10 cm
	P21	Injected cotton 5 cm
	P22	Injected cotton 10 cm
Interior wall insulation	P23	EPS 5 cm
	P24	EPS 10 cm
	P25	Mineral wool 5 cm
	P26	Mineral wool 10 cm
	P27	Cellulose 5 cm
	P28	Cellulose 10 cm
	P29	Cork 5 cm
	P30	Cork 10 cm
	P31	Sheep wool 5 cm
	P32	Sheep wool 10 cm
	P33	Cotton 5 cm
	P34	Cotton 10 cm
Exterior roof insulation	P35	XPS 8 cm
	P36	XPS 12 cm
Interior roof insulation	P37	EPS 4 cm
	P38	EPS 8 cm
	P39	Mineral wool 4 cm
	P40	Mineral wool 8 cm
Intervention on openings	P41	PVC frame; 4/12/4 glazing
	P42	PVC frame; 4/16/4 low-e glazing
	P43	Aluminium frame with thermal break; 4/12/4 glazing
	P44	Aluminium frame with thermal break; 4/16/4 low-e glazing
Sun control and shading devices	P45	Articulated awning installation
	P46	Solar film installation
Airtightness improvement of openings	P47	Installation of weather strip, adhesive tape and elastic filler in office openings (doors and windows)

the most common main energy source), and in accordance with the expert criteria of the Catalan Institute of Energy (Institut Català de l'Energia (ICAEN)., 2016), a total of 58 energy retrofitting measures were selected: 47 primary measures (P), 5 secondary measures (S), 3 tertiary measures (T) and 2 improvement measure packages (PQ).

Primary measures (Table 4) were grouped into façade insulation, roof insulation, placement of sunscreen and reduction of infiltrations.

Secondary measures (Table 5) were related to renovation of existing heat pumps, substitution of existing lamps and upgrading of existing lifts.

Tertiary measures (Table 6) included implementation of control systems and raising users' awareness about office energy consumption. The method described in Yoon et al. (2018) was used to estimate the energy savings a control system may provide. According to the European Environment Agency (2013), raising users' awareness can provide savings of up to 20 %. In the context of Horizon 2020 EU.3.3.1 call, several projects were financed to implement and study the

Table 5
List of secondary energy retrofitting measures and their corresponding code.

Group of measures	Measure code	Description of the measure
Heat pump replacement	S1	Replacement of heat pumps with high-efficiency ones
Implementation of heat recovery ventilation	S2	Implementation of a heat recovery ventilation system
Lamp replacement	S3	Replacement of existing lamps with LED lamps
	S4	Replacement of the ballasts of fluorescent lamps with electronic ones
Lift replacement	S5	Replacement of the lift with a high-efficiency model

outcome of serious energy-saving games in the office environment. The ENTROPY project (Ramallo-González et al., 2018) achieved consumption reductions of 6.62 % in heating, 4.90 % in cooling and 20.11 % in lighting. The OrbEEt project (O'Connor et al., 2018) concluded that overall energy savings of between 16.88 % and 21.28 % could be achieved by changing users' behaviour, and the GreenPlay project (Csoknyai, Horváth, & Legardeur, 2018) found overall savings ranged from 1.9%–10.4% depending on the office. According to these results, two scenarios were devised depending on the users' engagement level: 10 % and 20 %.

Two improvement packages were devised: a comprehensive retrofitting package and a low-cost retrofitting package (Table 7). The comprehensive retrofitting package was designed to provide savings in the HVAC system, to promote synergies between primary (e.g. removing thermal bridges by enhancing the insulation of the entire thermal enclosure) and secondary measures (changing the existing HVAC system for another that is more efficient). In addition, the comprehensive package was adapted for office blocks and offices in industrial buildings, and for offices in residential buildings. Measures in the low-cost package were selected to provide significant energy savings with the least possible investment.

3.3. Evaluation of the life-cycle energy impact

Energy savings ($kWh/m^2{\cdot}year$) resulting from the implementation of energy retrofitting measures in the representative offices were obtained by applying Eq. (1).

Specific results of the evaluation of the life-cycle energy impact for each representative office and each energy retrofitting measure can be found in the Research data section.

3.4. Evaluation of the life-cycle economic impact

The initial investment cost of a retrofitting measure was calculated by breaking down each measure into the corresponding tasks and examining for each task its related materials, labour, tools, machinery and health and safety systems. Data were mostly obtained from two price databases of construction elements: the BEDEC database (Institut de Tecnologia de la Construcció de Catalunya - ITeC, 2019) and the price generator for construction (CYPE Ingenieros, 2018).

The extra investment cost was calculated by deducting the costs of a conventional measure from the initial investment cost. Costs to be deducted are listed in Table 8 (primary measures) and Table 9 (secondary measures).

The economic savings of each retrofitting measure were calculated according to Eq. (5). Table 10 summarizes the energy costs for each energy source obtained from rates for 2018 and 2019.

The payback period was calculated for both the initial investment cost and the extra investment cost, using Eqs. (7) and (8).

The Research data section contains specific results of the evaluation of the life-cycle economic impact for each representative office and each energy retrofitting measure.

3.5. Evaluation of the life-cycle environmental impact

The life-cycle environmental impact was calculated using SimaPro v9.0 software (SimaPro, 2019) and the ReCiPe 2016 v1.1 midpoint hierarchist method (Huijbregts et al., 2016). Following the

Table 6
List of tertiary energy retrofitting measures and their corresponding code.

Group of measures	Measure code	Description of the measure
Implementation of control systems	T1	Implementation of a lighting and HVAC control system
Raising users' awareness	T2	Actions to modify users' behaviour (low engagement)
	T3	Actions to modify users' behaviour (high engagement)

Table 7
List of improvement measure packages and their corresponding code.

Description of the pack of measures	Pack of measures code	Measure code	Description of the measure
Comprehensive refurbishment	PQ1-B (for office blocks or offices in industrial buildings)	P1	Exterior wall insulation with EPS 6 cm
		P35	Exterior roof insulation with XPS 8 cm
		P42	Replacement of existing windows with new ones with PVC frame and 4/16/4 low-e glazing
		S1	Replacement of the heat pumps with high-efficiency ones
		S2	Integration of a heat recovery ventilation system
	PQ1-R (for offices in residential buildings)	P23	Interior wall insulation with EPS 5 cm
		P42	Replacement of existing windows with new ones with PVC frame and 4/16/4 low-e glazing
		S1	Replacement of the heat pumps with high-efficiency ones
Low-cost refurbishment	PQ2	P46	Solar film installation
		P47	Installation of weather strip, adhesive tape, and elastic filler in office openings (doors and windows)
		S3	Replacement of existing lamps for LED lamps

Table 8
Costs to be deducted when the extra investment cost is calculated for primary measures.

Energy retrofitting measure	Code	Costs to be deducted from the total initial investment cost
Exterior wall insulation	P1-P8	Cost of scaffolding, finishing and other elements of conventional retrofitting, such as the repair and treatment of the façade and the placement of a coating before the exterior finishing paint
Cavity wall insulation	P9-P22	Cost of paint finishing
Interior wall insulation	P23-P34	Cost of paint finishing
Exterior roof insulation	P35-P36	Cost of waterproofing, mortar, pavement and roof finishing
Interior roof insulation	P37-P40	Cost of ceiling and finishing
Intervention on openings	P41-P44	The extra investment cost is the difference between installing a double glazing 4/12/4 or low-e 4/16/4 compared to simpler double glazing 4/6/4
Articulated awning installation	P45	No deductions, all tasks and items required are due to the implementation of the energy retrofitting measure
Solar film installation	P46	No deductions, all tasks and items required are due to the implementation of the energy retrofitting measure
Airtightness improvement of openings	P47	No deductions, all tasks and items required are due to the implementation of the energy retrofitting measure

recommendation in Martínez-Rocamora, Solís-Guzmán, and Marrero (2016), Ecoinvent 3.5 (Ecoinvent., 2018) (allocation at the point of substitution) was used to estimate the environmental impact of energy retrofitting measures.

The construction databases that were used to characterize energy retrofitting-related tasks were those offered by CYPE Ingenieros (2018) and Institut de Tecnologia de la Construcció de Catalunya - ITeC (2019). The average transport distance for mineral products was assumed to be 50 km. The remaining building products were assumed to have an average transport distance of 300 km (Gantner et al., 2015). Transport of machinery to the construction site was assumed to be negligible. Complete results and life-cycle inventory data are available in the Research data section.

3.6. Model implementation

To design a user-friendly tool, potential users of the model were identified, using the guidance in Jensen et al. (2018). Identified users include owners and managers of office buildings, building refurbishment technicians and energy service companies. They are mainly interested in identifying the most economically viable renovation measure and its environmental impact for a particular office.

As shown in Fig. 2, the user first enters basic data on the office into the user-friendly interface. These basic data correspond to the variables selected during the identification of reference offices (location, period of construction, surface area of building envelopes, volume of the habitable zone, window glazing type, heating and domestic hot water energy sources, etc.).

Then, the user selects the energy retrofitting measures to be simulated. Results are shown in a table in which the selected individualized energy retrofitting measures are provided along with their energy, economic and environmental impact. Results are also shown graphically by means of a bubble chart for each typology of retrofitting measure (primary, secondary, tertiary or packages of measures).

By way of example, Figs. 3–6 respectively display the performance of primary, secondary and tertiary measures and packages of measures for the B5 representative office. The payback period and the initial investment cost are shown on the X and Y axes of the chart. The size of the bubble represents the energy savings that the retrofitting measure provides. Finally, the global carbon footprint of each energy renovation measure is shown on a colour scale, where green represents the highest reduction in CO_{2eq} emissions, yellow stands for a neutral impact and red is the highest increase in CO_{2eq} emissions.

Table 10
Energy price by energy source.

Energy source	Energy cost *(€/kWh)
Electricity	0.10980
Natural gas	0.05199
LPG	0.08720

* VAT not included.

3.7. Discussion of the results

The life-cycle energy, economic and environmental impact was evaluated for each energy retrofitting measure (Section 3.7.1) and office typology (Section 3.7.2). Complete results are presented in the Research data section.

3.7.1. Results by energy retrofitting measure

The results of each energy retrofitting measure are analysed in the following section, regardless of the office type.

3.7.1.1. Life-cycle energy impact results. For a study period of 20 years, operating energy consumption is the predominant stage in the life-cycle energy impact. An analysis of the Cumulative Energy Demand showed that the operational phase accounted for 97.98 % of the life-cycle primary energy demand. The embodied energy of the retrofitting measure represented just 2.02 % of the total Cumulative Energy Demand. For example, in representative office B5, the contribution of the operating phase to the Cumulative Energy Demand ranged from 88.66 % to 99.99 %, depending on the energy retrofitting measure. Because of these high contributions, only final energy savings during the operating phase are analysed.

Energy savings were found to be highly dependent on the energy retrofitting measure. However, on average all measures reduced energy consumption. The results are summarized in Fig. 7 by representing the

Table 9
Costs to be deducted when the extra investment cost is calculated for secondary measures.

Energy retrofitting measure	Code	Costs to be deducted from the total initial investment cost
Heat pump replacement	S1	The extra investment cost is the difference between purchasing a high-efficiency heat pump and a conventional one
Implementation of a heat recovery system	S2	There are no deductions. All tasks and items required are due to the installation measure
Replacement of existing lamps with LED lamps	S3	The extra investment cost is the difference between replacing the existing lamp with a LED lamp instead of a fluorescent one
Replacement of conventional ballasts with electronic ones	S4	No deductions, practically all ballasts sold today are electronic
Lift replacement	S5	The extra investment cost is the difference between purchasing a high-efficiency lift and a conventional one

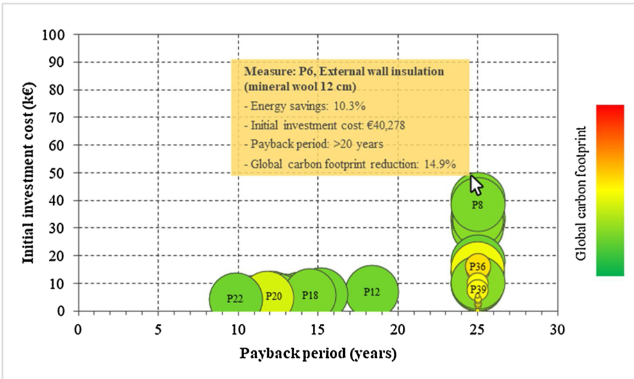

Fig. 3. Bubble chart of the performance (payback period, initial investment cost and global carbon footprint reduction) of primary measures for the B5 representative office.

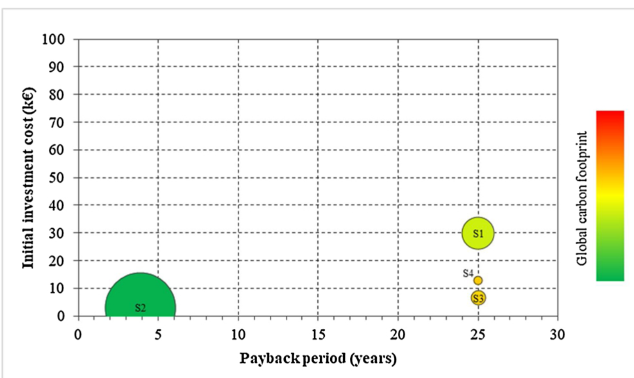

Fig. 4. Bubble chart of the performance (payback period, initial investment cost and global carbon footprint reduction) of secondary measures for the B5 representative office.

percentage of cases (a case being an energy retrofitting measure applied to a representative office) for each energy retrofitting measure category (primary, secondary and tertiary) in each energy savings interval.

Primary measures were found to provide energy savings in 99.67 % of the cases (Fig. 7). The exceptions were modern offices with high thermal performance windows installed in the base state. The average final energy savings of primary measures was 6.11 %. Exterior wall insulation provided higher energy savings (8.81 %) than cavity wall (5.35 %) and interior wall insulation (5.41 %) because of thermal bridges. Similarly, exterior roof insulation (8.84 %) provided higher energy savings than interior roof insulation (6.41 %). Window replacements performed differently depending on the glazing and the frame. A PVC frame and low-e glazing was the most energy-effective option (8.43 %). Solar films provided lower energy reductions (2.33 %) as they only affected the glazing's thermal performance. The installation of awnings should be studied case by case, as the office location and orientation of openings can lead to favourable or unfavourable results. Airtightness improvement provided a slight reduction in energy consumption (0.29 %).

Secondary measures were found to produce high energy savings (11.88 %). In all cases, the most effective secondary measures were found to be heat pump replacement (19.88 %), lamp replacement by LEDs (15.15 %), and implementation of heat recovery ventilation (11.02 %). It should be noted that the results for the heat pump and heat recovery ventilation system were highly dependent on the existing system. Replacement of conventional ballasts with electronic ones (7.33 %) and lift replacement (6.00 %) were found to provide lower energy savings.

In relation to tertiary measures and as expected, raising the users' awareness with high engagement was the most effective measure, with relative energy savings of 20 %.

Finally, comprehensive and low-cost refurbishment packages of measures provided savings of 31.26 % and 17.28 %, respectively.

3.7.1.2. Life-cycle economic impact results. Regarding primary measures, exterior wall insulation proved to be profitable in just one scenario where the effect of thermal bridges played a central role in wall heat transfer. In the other cases, even though this measure provided significant energy savings, its high cost reduced its profitability to the

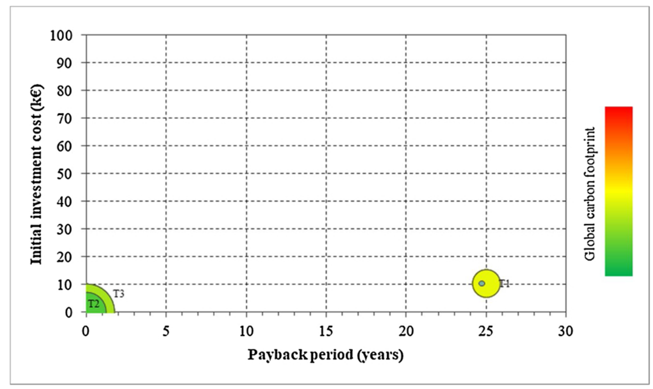

Fig. 5. Bubble chart of the performance (payback period, initial investment cost and global carbon footprint reduction) of tertiary measures for the B5 representative office.

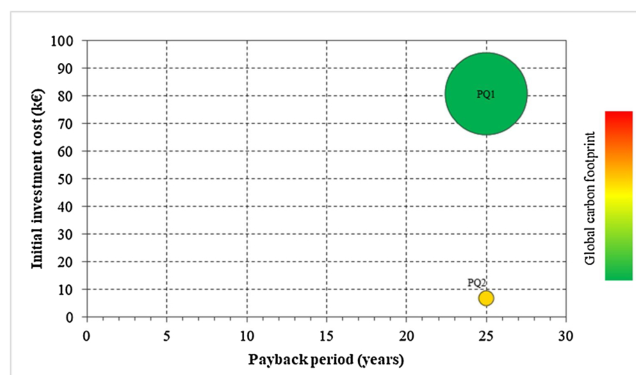

Fig. 6. Bubble chart of the performance (payback period, initial investment cost and global carbon footprint reduction) of packages of measures for the B5 representative office.

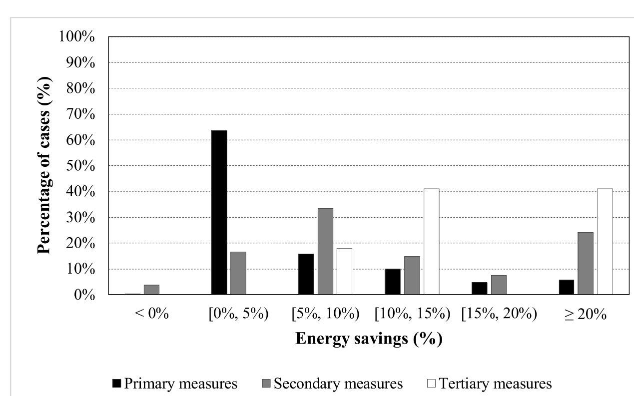

Fig. 7. Percentage of cases in ranges of average energy savings provided by primary, secondary and tertiary measures in office blocks and offices in industrial buildings, and offices in residential buildings.

extent that it generally did not get to break-even point. Doubling the thickness of the insulation layer (from 6 to 12 cm) slightly increased the energy savings, but the payback period was prolonged due to the higher investment cost. Cavity wall insulation was the most profitable primary energy retrofitting measure, which was cost-effective in ten out of sixteen offices. This is because the initial investment cost was low and the energy savings were high enough, even though they were lower than those offered by exterior wall insulation. Unlike exterior wall insulation, cavity wall insulation seemed to perform better with a higher insulation thickness. Interior wall insulation was not recommendable from an economic perspective as its costs are higher than cavity wall insulation, while the energy savings are similar. Roof insulation was only advisable in offices with high-transmittance roofs. Between interior and exterior insulation, the former was preferred because the initial investment cost to externally insulate a roof is higher than the extra reduction in energy consumption. Options with a higher thickness of insulation layer were more cost-effective. Intervention on openings was economically unadvisable in all cases. Installation of solar films was also unprofitable, although in specific cases it could become profitable (e.g. residential offices with single glazing windows). The installation of awnings and improvement in the airtightness of openings were economically unadvisable, in general.

Secondary measures were generally profitable because of their close relation with energy consumption and their relative low investment cost. When the number of cases were distributed according to the payback period and type of measure (Fig. 8), secondary measures were unprofitable for the first 20 years in 38.89 % of cases. Heat pump replacement and implementation of heating recovery ventilation systems were only recommended if existing systems were old and/or inefficient. Lamp replacement was consistently found to be the most profitable measure (with payback periods as short as under a year) because it considerably reduced lighting consumption (55.0 % and 22.6 %) and the initial investment costs were low. When possible, the installation of LEDs was preferred over replacement with electronic ballasts. Lastly, the replacement of the lift was only financially advisable in big offices.

According to the results, the implementation of control systems was not cost-effective in any of the representative offices. However, measures to raise users' awareness were always cost-effective, because their implementation was cost free.

The integral refurbishment package was economically advisable in just one representative office, because the primary measures that make up the package were also unprofitable (exterior wall insulation, exterior roof insulation and intervention on openings). In contrast, the low-cost option was profitable in all offices, except the office that had been recently built according to new energy-efficiency regulations.

3.7.1.3. Life-cycle environmental impact results. Most primary measures

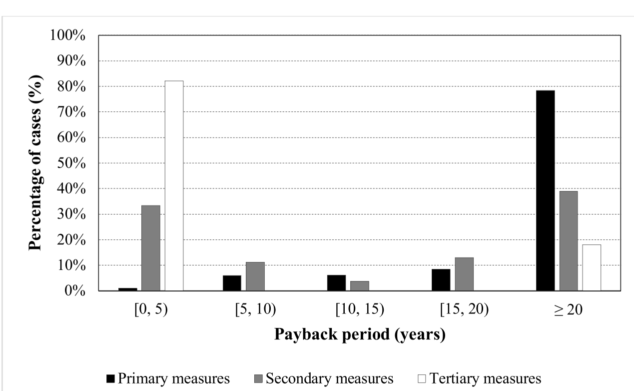

Fig. 8. Percentage of cases in ranges of average payback period provided by primary, secondary and tertiary measures in office blocks and offices in industrial buildings, and offices in residential buildings.

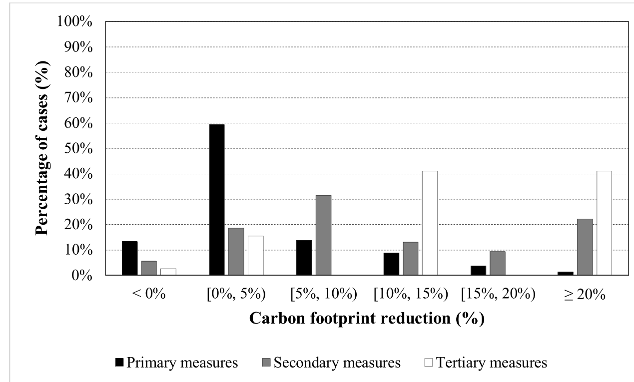

Fig. 9. Percentage of cases in ranges of average carbon footprint reduction provided by primary, secondary and tertiary measures in office blocks and offices in industrial buildings, and offices in residential buildings.

reduced life-cycle greenhouse gas emissions when a reference study period of 20 years was considered. As shown in Fig. 9, which represents the distribution of cases (i.e. a measure applied to a representative office) according to the average carbon footprint reduction, there were a few exceptions that accounted for 13.13 % of cases. These included modern offices with low energy consumption, in which the energy savings produced by primary energy saving measures did not offset the life-cycle impact of the measure. In addition, primary measures usually have lifetimes of over 20 years, so do not need to be replaced just after the end of the reference study period.

Thicker wall insulation layers showed slightly higher reductions in life-cycle CO_{2eq} emissions (0.55 extra percentage points on average), as savings increased more than the impact caused by the required materials and processes. However, the type of insulation material did not significantly modify the life-cycle environmental impact of the retrofitting measures as its contribution to the impact of the measure was low. Exterior wall insulation was more effective at reducing life-cycle carbon dioxide emissions (a carbon footprint reduction of 6.01 %) than cavity and interior wall insulation. When exterior wall insulation was not possible (e.g. offices located in residential buildings), cavity wall insulation, with a carbon footprint reduction of 4.93 %, was the recommended retrofitting measure. Interior wall insulation offered lower reductions in CO_{2eq} emissions (4.01 %) as a result of lower energy savings (than exterior wall insulation) and higher material requirements (than cavity wall insulation). Roof insulation provided lower reductions in greenhouse gas emissions than wall insulation measures. Interior roof insulation (carbon footprint reduction of 3.06 %) was preferable. Although it provided lower emission reductions during its operational life, it was less material- and energy-intensive than exterior wall insulation. In this case, the carbon footprint reduction amounted to 1.97 %.

Window replacement was the most effective intervention on openings, with a reduction of 5.95 % for low-e double glazing and PVC frames. Aluminium frames had a higher environmental impact than PVC frames due to higher energy consumption during the manufacturing process. When window replacement was not possible, solar films were recommended, even though their emissions reduction was lower (carbon footprint reduction of 2.21 %). As explained in the life-cycle energy impact results, the installation of awnings led to positive or negative results (reductions or increases in emissions) depending on the office location and the orientation of openings.

Secondary measures offered the highest life-cycle emission reductions because of the high energy savings they provided. When the existing system was old and inefficient, carbon emission reductions for the heat pump and heat recovery ventilation system were found to be 18.58 % and 8.47 %, respectively. Replacement of lamps with LEDs was consistently found to be a good measure that reduced greenhouse gas

Table 11
Energy retrofitting measures with the highest carbon footprint reductions for office blocks and offices in industrial buildings.

Office reference	Building regulation	Energy retrofitting measure		Life-cycle carbon footprint reduction (%)	Operational energy savings reduction (%)	Initial investment cost (€)	Payback period (years)
B1	None	P*	P38	22.26	24.49	9,094.97	14.07
		S*	S2	7.74	8.08	1,406.03	6.01
		T*	T3	20.00	20.00	0.00	0.00
B2	None	P	P6	4.00	7.14	418,639.81	> 20
		S	S1	9.29	9.42	209,185.33	> 20
		T	T3	20.00	20.00	0.00	0.00
B3	NBE-CT 79	P	P6	5.22	8.33	112,872.30	> 20
		S	S3	27.25	28.28	15,272.86	2.95
		T	T3	20.00	20.00	0.00	0.00
B4	NBE-CT 79	P	P42	24.41	29.33	3,166.68	> 20
		S	S2	11.78	12.89	877.91	> 20
		T	T3	20.00	20.00	0.00	0.00
B5	NBE-CT 79	P	P10	16.29	22.87	17,862.34	> 20
		S	S2	28.23	38.12	2,922.75	3.87
		T	T3	20.00	20.00	0.00	0.00
B6	TBC	P	P22	0.72	1.11	1,635.47	> 20
		S	S3	29.51	30.62	4,957.50	2.92
		T	T3	20.00	20.00	0.00	0.00
B7	NBE-CT 79	P	P38	5.93	12.03	9,255.71	> 20
		S	S1	26.34	26.32	6,412.74	> 20
		T	T3	20.00	20.00	0.00	0.00

* P stands for primary measures, S for secondary measures and T for tertiary measures.

emissions by 14.44 % on average. From an environmental perspective, lamp replacement by LEDs was preferred over the replacement of conventional ballasts with electronic ones (average CO_{2eq} reduction of 6.11 %). The greatest advantage of LED lighting is that it reduces energy consumption by 55 % compared to a conventional lamp. Finally, replacement of the original lift with a high-efficiency model resulted in greenhouse gas emissions savings of 4.89 %, although it could not compete with the other secondary measures.

The implementation of control systems was not an environmentally profitable option for small offices, mainly because the energy savings (5% of the total office energy consumption) were very low. In large offices, the equipment that was needed was similar, but the energy savings (in absolute terms) increased. Thus, this option was advisable from the life-cycle environmental perspective. In contrast, measures to raise users' awareness were always environmentally friendly as the impact of their implementation was negligible. In fact, raising users' awareness was the energy retrofitting measure with the highest CO_{2eq} savings (10 % for low and 20 % for high users' engagement) because of the initial assumptions.

As expected, the comprehensive refurbishment package led to higher greenhouse gas emission reductions (22.54 %) than the low-cost option (16.53 %).

3.7.2. Results by office typology

In general, implementation of energy retrofitting measures in office blocks and offices in industrial buildings was found to obtain lower life-cycle carbon emission reductions, lower energy savings and higher payback periods than offices in residential buildings. This could be explained by the fact that representative offices in residential buildings tend to be older. However, energy savings for primary measures were higher in office blocks and offices in industrial buildings because they have a higher degree of external exposure.

From an energy perspective, the most advisable primary energy retrofitting measure for office blocks and offices in industrial buildings was roof insulation. In contrast, for offices in residential buildings, it was more advisable to act on openings or to apply cavity wall insulation. Considering life-cycle emissions, the most environmentally friendly measure for all the offices was wall insulation (exterior or cavity wall depending on the representative office), as its implementation was less resource- and energy-intensive than roof insulation. In relation to secondary measures, heat pump replacement and replacement of lamps with LED bulbs were the most appropriate measures (considering energy savings and life-cycle CO_{2eq} emission reductions) for both office typologies.

Office age was found to be the characteristic that had the most influence on the performance of energy retrofitting measures, but its impact varied depending on the type of measure.

For primary and secondary measures, energy savings were found to rise with the age of the buildings. By way of example and for primary measures, energy savings were much greater in old offices (7.92 %) than in modern ones (2.62 %), due to the lower insulation levels in older offices. Energy savings of tertiary measures were not affected by office age. The life-cycle economic impact results showed a similar trend for primary measures, as they never achieved break-even during the first 20 years in new offices (built after 2007; Spain, 2006), while half of them were cost effective in the oldest ones (built prior to 1981; Spain, 1979). Life-cycle environmental impact results were equal to those of the energy savings.

Finally, the energy retrofitting measures that were most effective at reducing the life-cycle carbon footprint are presented for each representative office in Tables 11 and 12 , together with their operational energy savings reduction, initial investment cost and payback periods. For the oldest offices (i.e. built before 1981), the most advisable primary and secondary measures were a 10-cm layer of cavity wall insulation (average life-cycle CO_{2eq} reduction of 9.47 %) and heat pump replacement (average life-cycle CO_{2eq} reduction of 21.63 %). For offices built between 1981 and 2006, the intervention on openings with PVC frames and low-e glazing (average life-cycle emissions of 5.87 %) was the primary measure recommended for its environmental impact. Regarding secondary measures, heat pump replacement and the implementation of a heat recovery ventilation system were recommended (average life-cycle GHG emissions of 15.85 % and 17.78 %, respectively). For the newest offices built after 2006, the recommended measures were also intervention on openings with a PVC frame and low-e glazing (6.52 %), heat pump replacement (28.80 %) and the implementation of a heat recovery ventilation system (22.31 %). These measures were only advisable when the pre-existing system was inefficient.

4. Conclusions

This paper describes the development of a model to identify life-

Table 12
Energy retrofitting measures with the highest carbon footprint reductions for offices in residential buildings.

Office reference	Building regulation	Energy retrofitting measure		Life-cycle carbon footprint reduction (%)	Operational energy savings reduction (%)	Initial investment cost (€)	Payback period (years)
R1	None	P*	P42	11.58	12.92	5,224.64	> 20
		S*	S1	23.72	24.02	5,476.38	> 20
		T*	T3	20.00	20.00	0.00	0.00
R2	None	P	P10	28.08	29.44	2,436.11	> 20
		S	S3	11.35	11.45	67.68	0.85
		T	T3	20.00	20.00	0.00	0.00
R3	None	P	P10	17.40	18.48	4,471.17	> 20
		S	S1	23.50	23.90	3,397.62	16.63
		T	T3	20.00	20.00	0.00	0.00
R4	NBE-CT 79	P	P45	6.88	12.96	1,607.36	> 20
		S	S1	23.12	24.91	2,191.19	> 20
		T	T3	20.00	20.00	0.00	0.00
R5	NBE-CT 79	P	P45	15.79	19.64	2,411.04	> 20
		S	S1	19.36	20.12	2,060.91	> 20
		T	T3	20.00	20.00	0.00	0.00
R6	None	P	P45	9.91	11.89	803.68	> 20
		S	S3	8.23	8.67	121.58	4.12
		T	T3	20.00	20.00	0.00	0.00
R7	NBE-CT 79	P	P42	1.30	2.78	488.35	> 20
		S	S3	21.79	22.69	3,108.81	3.21
		T	T3	20.00	20.00	0.00	0.00
R8	None	P	P42	5.75	6.96	3,492.39	> 20
		S	S1	44.06	44.13	1,642.91	6.13
		T	T3	20.00	20.00	0.00	0.00
R9	TBC	P	P42	6.52	12.14	21,920.93	> 20
		S	S1	28.80	29.10	6,089.40	18.79
		T	T3	20.00	20.00	0.00	0.00

* P stands for primary measures, S for secondary measures and T for tertiary measures.

cycle environmental and cost-effective energy retrofitting measures for the entire office stock through the assessment of their energy, economic and environmental impacts. Unlike previous research in this field, the methodology is based on real buildings through the analysis of national energy performance certificate databases, as they are a good source of information on the characteristics of the building stock. Therefore, the model can easily be replicated in different geographical areas.

The model first identifies a set of reference offices using the k-means clustering-based grouping technique applied to the energy performance certificate database. For each representative office, a database gathers the life-cycle energy, economic and environmental impacts of a number of energy renovation measures. Given the main characteristics of the office to be assessed, the model provides tailored information about the energy, economic and environmental performance of the selected energy renovation measures along with the representativeness of the results.

The findings of this research were integrated into a user-friendly interface to support decision-makers during the energy retrofitting process. The tool is ready to be implemented within the framework of public energy agencies or city councils. This will definitely contribute to overcoming barriers to energy refurbishment, such as a lack of individualized information.

The case study is based on the analysis of over 13,000 energy performance certificates related to offices in the Mediterranean climatic zone. Another key feature is that a considerable range of individual energy renovation measures were analysed (47 primary measures, 5 secondary measures, 3 tertiary measures and 2 packages of improvement measures).

Optimal measures were found to vary depending on the office typology. The combined impact of product, construction and end-of-life stages was significantly lower than that avoided in the use stage (53.9 % of emissions savings, on average). Generally, optimal measures from an environmental perspective were not optimal from an economic perspective within a 20-year period. It was found that in 87.7 % of cases, energy retrofitting measures reduce life-cycle CO_{2eq} emissions while only 28.0 % of the total cases are economically viable. In almost all cases (99.5 %), cost-effective measures also provided life-cycle greenhouse gas emission reductions.

Research data

Gangolells, M., Gaspar, K., Casals, M., Ferré-Bigorra, J., Forcada, N., Macarulla, M. (2020). *Model for identifying life-cycle environmental and cost-effective energy retrofitting measures for the existing office stock.* Mendeley Data, v1. 10.17632/r87947jmw8.1.

Gangolells, M., Gaspar, K., Casals, M., Ferré-Bigorra, J., Forcada, N., Macarulla, M. (2020). *LCA inventory analysis related to the implementation of energy retrofitting measures in the existing office stock.* Mendeley Data, v1. 10.17632/j8yvdjgp4t.1.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the Spanish Ministry of Economy, Industry and Competitiveness under R&D project EOFF, reference no. BIA2016-75382-R (AEI/FEDER, UE). The Catalan Institute of Energy (ICAEN) is gratefully acknowledged for allowing access to the energy performance certificates database.

References

Almeida, M., & Ferreira, M. (2017). Cost effective energy and carbon emissions optimization in building renovation (Annex 56). *Energy and Buildings, 152*, 718–738. https://doi.org/10.1016/j.enbuild.2017.07.050.

Bournas, I., Abugabbara, M., Balcerzak, A., Dubois, M. C., & Javed, S. (2016). Energy renovation of an office building using a holistic design approach. *Journal of Building Engineering, 7*, 194–206. https://doi.org/10.1016/j.jobe.2016.06.010.

Brøgger, M., & Wittchen, K. B. (2018). Estimating the energy-saving potential in national

building stocks – A methodology review. *Renewable and Sustainable Energy Reviews, 82*(July 2017), 1489–1496. https://doi.org/10.1016/j.rser.2017.05.239.
Buildings Performance Institute Europe (BPIE) (2011). *Europe's buildings under the microscope.* (Accessed 21 January 2020) http://bpie.eu/wp-content/uploads/2015/10/HR_EU_B_under_microscope_study.pdf.
Buildings Performance Institute Europe (BPIE) (2017). *Factsheet. 97% of buildings in the EU need to be upgraded.* (Accessed 21 January 2020) http://bpie.eu/publication/97-of-buildings-in-the-eu-need-to-be-upgraded/.
Buildings Performance Institute Europe (BPIE) (2019). *Discussion paper. Buildings should be at heart of the European Green Deal. Here's why.* (Accessed 21 January 2020) http://bpie.eu/wp-content/uploads/2019/12/EU-Green-Deal-buildings_BPIE_Discussionpaper_Dec2019.pdf/.
Congedo, P. M., Baglivo, C., D'Agostino, D., & Zacà, I. (2015). Cost-optimal design for nearly zero energy office buildings located in warm climates. *Energy, 91*(244), 967–982. https://doi.org/10.1016/j.energy.2015.08.078.
Congedo, P. M., Baglivo, C., & Centonze, G. (2020). Walls comparative evaluation for the thermal performance improvement of low-rise residential buildings in warm Mediterranean climate. *Journal of Building Engineering, 28*(May 2019), https://doi.org/10.1016/j.jobe.2019.101059.
Csoknyai, T., Horváth, M., & Legardeur, J. (2018). *Game to promote energy efficiency actions (GreenPlay). D6.3 Assessment of the solution impact on environmental issues and energy savings.* (Accessed 04 May 2020) http://www.greenplay-project.eu/wp-content/uploads/2018/12/D6.3_Environmental_impact_BME_vf.pdf.
CYPE Ingenieros, S. A. (2018). *Generador de precios de la construcción. España.* (Accessed 13 March 2019) http://www.generadordeprecios.info/.
Dotzler, C., Botzler, S., Kierdorf, D., & Lang, W. (2018). Methods for optimising energy efficiency and renovation processes of complex public properties. *Energy and Buildings, 164*, 254–265. https://doi.org/10.1016/j.enbuild.2017.12.060.
Ecoinvent (2018). *Ecoinvent 3.5. Zurich.* (Accessed 29 April 2019) https://www.ecoinvent.org/database/older-versions/ecoinvent-35/ecoinvent-35.html.
Emami, N., Heinonen, J., Marteinsson, B., Säynäjoki, A., Junnonen, J. M., Laine, J., ... Junnila, S. (2019). A life cycle assessment of two residential buildings using two different LCA database-software combinations: Recognizing uniformities and inconsistencies. *Buildings, 9*(1), 1–20. https://doi.org/10.3390/buildings9010020.
European Commission (2012). *Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating.* Official Journal of the European Union28. https://doi.org/10.3000/1977091X.C_2012.115.eng.
European Commission (2018a). *Energy, market analysis. Retail electricity and gas prices.* (Accessed 5 December 2019) https://ec.europa.eu/energy/en/data-analysis/market-analysis.
European Commission (2019a). *Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions. The European green deal. COM (2019) 640 final.* Official Journal of the European Union. (Accessed 5 December 2019) https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf.
European Commission (2018b). *Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.* Official Journal of the European Union75–91 2018(April). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN (Accessed 5 December 2019).
European Commission (2019b). *Regulation (EU) 2017/1369 of the European Parliament and of the Council of 4 July 2017 setting a framework for energy labelling and repealing Directive 2010/30/EU (OJ L 198.* Official Journal of the European Union75. 6(2015), (Accessed 5 December 2019) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019H0786&rid=5.
European Committee for Standardization (CEN) (2011). *Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. CEN standard 15978.* Brussels: European Committee for Standardization (CEN).
European Committee for Standardization (CEN) (2019). *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. CEN standard 15804.* Brussels: European Committee for Standardization (CEN).
European Environment Agency (2013). *Achieving energy efficiency through behaviour change: What does it take?* Luxembourg: Publications Office of the European Unionhttps://doi.org/10.2800/49941 2013.
European Parliament (2019). *The European Parliament declares climate emergency.* (Accessed 21 January 2020) https://www.europarl.europa.eu/news/en/press-room/20191121IPR67110/the-european-parliament-declares-climate-emergency/.
European Union (2019). *EU energy in figures, Statistical Pocketbook 2019.* https://doi.org/10.2833/197947.
Gangolells, M., Casals, M., Forcada, N., Macarulla, M., & Cuerva, E. (2016). Energy mapping of existing building stock in Spain. *Journal of Cleaner Production, 112*, 3895–3904. https://doi.org/10.1016/j.jclepro.2015.05.105.
Gangolells, M., Casals, M., Ferré-Bigorra, J., Forcada, N., Macarulla, M., Gaspar, K., ... Tejedor, B. (2019). Energy benchmarking of existing office stock in Spain: Trends and drivers. *Sustainability (Switzerland), 11*(22), https://doi.org/10.3390/su11226356.
Gangolells, M., Casals, M., Ferré-Bigorra, J., Forcada, N., Macarulla, M., Gaspar, K., ... Tejedor, B. (2020). Office representatives for cost-optimal energy retrofitting analysis: A novel approach using cluster analysis of energy performance certificate databases. *Energy and Buildings, 206*, 109557. https://doi.org/10.1016/j.enbuild.2019.109557.
Gantner, J., Wittstock, B., Lenz, K., Fischer, M., Sedlbauer, K., Anderson, J., ... Sjöström, C. (2015). *EeBGuide guidance document part B: Buildings. Operational guidance for life cycle assessment studies of the energy efficient building initiative.* Stuttgart: FRAUNHOFER VERLAG.
Gustafsson, M., Dipasquale, C., Poppi, S., Bellini, A., Fedrizzi, R., Bales, C., ... Holmberg, S. (2017). Economic and environmental analysis of energy renovation packages for European office buildings. *Energy and Buildings, 148*, 155–165. https://doi.org/10.1016/j.enbuild.2017.04.079.
Hashempour, N., Taherkhani, R., & Mahdikhani, M. (2020). Energy performance optimization of existing buildings: A literature review. *Sustainable Cities and Society, 54*(November 2019), 101967. https://doi.org/10.1016/j.scs.2019.101967.
Hjortling, C., Björk, F., Berg, M., & Klintberg, T. (2017). Energy mapping of existing building stock in Sweden – Analysis of data from Energy Performance Certificates. *Energy and Buildings, 153*, 341–355. https://doi.org/10.1016/j.enbuild.2017.06.073.
Huijbregts, M., Steinmann, Z. J. N., Elshout, P. M. F. M., Stam, G., Verones, F., Vieira, M. D. M., ... van Zelm, R. (2016). *ReCiPe 2016.* National Institute for Public Health and the Environment194. https://doi.org/10.1007/s11367-016-1246-y.
Institut Català de l'Energia (ICAEN) (2016). *Rehabilitació energètica d'edificis. Col•lecció quadern pràctic número 10.* 159. (Accessed 18 February 2019) http://icaen.gencat.cat/web/.content/10_ICAEN/17_publicacions_informes/04_coleccio_QuadernPractic/quadern_practic/arxius/10_rehabilitacio_edificis.pdf.
Institut de Tecnologia de la Construcció de Catalunya - ITeC (2019). *BEDEC database 2019.* (Accessed 23 March 2019) https://metabase.itec.cat/vide/ca/bedec.
International Organization for Standardization (ISO) (2006). *Environmental management — Life cycle assessment — Requirements and guidelines. ISO standard 14044.* Geneva: International Organization for Standardization.
International Organization for Standardization (ISO) (2006). *Environmental management — Life cycle assessment — Principles and framework. ISO Standard 14040.* Geneva: International Organization for Standardization (ISO).
Jensen, P. A., Maslesa, E., Berg, J. B., & Thuesen, C. (2018). 10 questions concerning sustainable building renovation. *Building and Environment, 143*(May), 130–137. https://doi.org/10.1016/j.buildenv.2018.06.051.
Jradi, M., Veje, C., & Jørgensen, B. N. (2017). Deep energy renovation of the Mærsk office building in Denmark using a holistic design approach. *Energy and Buildings, 151*, 306–319. https://doi.org/10.1016/j.enbuild.2017.06.047 2017.
Krejcie, R. V., & Morgan, D. W. (1970). Determining sample size for research activities. *Educational and Psychological Measurement, 30*(3), 607–610. https://doi.org/10.1177/001316447003000308.
Martínez-Rocamora, A., Solís-Guzmán, J., & Marrero, M. (2016). LCA databases focused on construction materials: A review. *Renewable and Sustainable Energy Reviews, 58*, 565–573. https://doi.org/10.1016/j.rser.2015.12.243.
Mata, É., Kalagasidis, A. S., & Johnsson, F. (2018). Contributions of building retrofitting in five member states to EU targets for energy savings. *Renewable and Sustainable Energy Reviews, 93*(May), 759–774. https://doi.org/10.1016/j.rser.2018.05.014.
Niemelä, T., Levy, K., Kosonen, R., & Jokisalo, J. (2017). Cost-optimal renovation solutions to maximize environmental performance, indoor thermal conditions and productivity of office buildings in cold climate. *Sustainable Cities and Society, 32*(April), 417–434. https://doi.org/10.1016/j.scs.2017.04.009.
O'Connor, S., Dunwell, I., Utz, W., Tsatsakis, K., Anastasios, T., Nikos, V., ... Gómez, M. (2018). *Organizational behaviour improvement for energy efficient administrative public office (OrbEEt). D4.6 report on Pilot Operation and validation of OrbEEt framework*. (Accessed 04 May 2020) https://orbeet.eu/wp-content/uploads/2018/04/D4.6-OrbEEt-Report-on-Pilot-Operation-Validation-Final1.pdf.
Ott, W., Bolliger, R., Ritter, V., Citherlet, S., Lasvaux, S., Favre, D., ... Ferrari, S. (2017). *Methodology for cost-effective energy and carbon emissions optimization in building renovation (Annex 56). Energy in buildings and communities programme.* (Accessed 28 March 2019) https://www.iea-ebc.org/Data/publications/EBC_Annex_56_Methodology_Cost-Effective_Energy_Carbon_Emissions_Optimization_Building_Renovation.pdf.
Patiño-Cambeiro, F., Armesto, J., Bastos, G., Prieto-López, J. I., & Patiño-Barbeito, F. (2019). Economic appraisal of energy efficiency renovations in tertiary buildings. *Sustainable Cities and Society, 47*(October 2018), 101503. https://doi.org/10.1016/j.scs.2019.101503.
Pikas, E., Thalfeldt, M., Kurnitski, J., & Liias, R. (2015). Extra cost analyses of two apartment buildings for achieving nearly zero and low energy buildings. *Energy, 84*, 623–633. https://doi.org/10.1016/j.energy.2015.03.026.
Pistore, L., Pernigotto, G., Cappelletti, F., Gasparella, A., & Romagnoni, P. (2019). A stepwise approach integrating feature selection, regression techniques and cluster analysis to identify primary retrofit interventions on large stocks of buildings. *Sustainable Cities and Society, 47*(January), 101438. https://doi.org/10.1016/j.scs.2019.101438.
Pomponi, F., Piroozfar, P. A. E., Southall, R., Ashton, P., Pirozfar, P., & Farr, E. R. P. (2015). Life cycle energy and carbon assessment of double skin façades for office refurbishments. *Energy and Buildings, 109*, 143–156. https://doi.org/10.1016/j.enbuild.2015.09.051.
Ramallo-González, A., Gori, G., Pokrić, M., Barque, M., Simsek, U., Genoud, D., ... González Vidal, A. (2018). *Design of an innovative energy-aware IT ecosystem for motivating behavioural changes towards the adoption of energy efficient lifestyles (ENTROPY). D5.3 performance evaluation and lessons learnt.* (Accessed 04 May 2020) https://entropy-project.eu/wp-content/uploads/2019/11/D5.3_compressed.pdf.
Rysanek, A. M., & Choudhary, R. (2013). Optimum building energy retrofits under technical and economic uncertainty. *Energy and Buildings, 57*, 324–337. https://doi.org/10.1016/j.enbuild.2012.10.027.
Schaefer, A., & Ghisi, E. (2016). Method for obtaining reference buildings. *Energy and Buildings, 128*, 660–672. https://doi.org/10.1016/j.enbuild.2016.07.001.
Sharif, S. A., & Hammad, A. (2019). Simulation-Based Multi-Objective Optimization of institutional building renovation considering energy consumption, Life-Cycle Cost and Life-Cycle Assessment. *Journal of Building Engineering, 21*(June 2018), 429–445. https://doi.org/10.1016/j.jobe.2018.11.006.

SimaPro (2019). *SimaPro 9.0.* (Accessed 29 April 2019) https://simapro.com/.
Spain (1979). *Royal decree 2429/1979, 6 July, approving the basic building norm on thermal conditions in buildings.* (Accessed 24 January 2020) https://www.boe.es/eli/es/rd/1979/07/06/2429.
Spain (2006). *Royal decree 314/2006, 17 March, approving the technical building code.* (Accessed 24 January 2020) https://www.boe.es/eli/es/rd/2006/03/17/314/con.
Spain (2013). *Royal Decree 235/2013, 5 April, approving the basic procedure for the certification of the energy efficiency of buildings.* (Accessed 24 January 2020) https://www.boe.es/eli/es/rd/2013/04/05/235.
Spain (2016). *Procedimientos para la certificación de edificios.* (Accessed 23 January 2019) https://energia.gob.es/desarrollo/EficienciaEnergetica/CertificacionEnergetica/DocumentosReconocidos/Paginas/procedimientos-certificacion-proyecto-terminados.aspx.
Stegnar, G., & Cerovšek, T. (2019). Information needs for progressive BIM methodology supporting the holistic energy renovation of office buildings. *Energy, 173*, 317–331. https://doi.org/10.1016/j.energy.2019.02.087.
United Nations (2015). *Transforming our world: The 2030 agenda for sustainable development.* Agenda for Sustainable Development web.pdf/ (Accessed 21 January 2020) https://sustainabledevelopment.un.org/content/documents/21252030.
Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy and Buildings, 135*, 286–301. https://doi.org/10.1016/j.enbuild.2016.11.042.
Wrålsen, B., O'Born, R., & Skaar, C. (2018). Life cycle assessment of an ambitious renovation of a Norwegian apartment building to nZEB standard. *Energy and Buildings, 177*, 197–206. https://doi.org/10.1016/j.enbuild.2018.07.036.
Yoon, S. H., Kim, S. Y., Park, G. H., Kim, Y. K., Cho, C. H., & Park, B. H. (2018). Multiple power-based building energy management system for efficient management of building energy. *Sustainable Cities and Society, 42*(May), 462–470. https://doi.org/10.1016/j.scs.2018.08.008.